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Grain refinement of Mg-Li-Al cast alloys by adding typical master alloys

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Abstract: Commercial Al-3Ti-1C and Al-5Ti-1B master alloys were added in order to refine the grains of Mg-Li-Al alloys. The effects of their addition levels on grain refinement of Mg-Li-Al cast alloy were investigated and the mechanism of the grain refinement was discussed. The results showed that the addition of Al-3Ti-1C master alloy reduced the grain size of LA141 cast alloy from 900 μm to 400 μm, while the addition of Al-5Ti-1B master alloy reduced the grain size of LA51 cast alloy from 500 μm to 240 μm. The grain refining mechanism was the heterogeneity nucleation of TiC and TiB_2, because of less than 10% mismatches of TiC/β-Li and TiB_2/α-Mg.
Key words: magnesium lithium alloy; master alloy; grain refinement

1 Introduction

Mg-Li alloy is one of the lightest magnesium alloys. It has lower c/a value than Mg-Al or Mg-Zn alloys. Especially, when the content of Li is over 5.7% (mass fraction) the β-Li phase with body center cubic (BCC) structure occurs. It has been used for some aeronautic and astronautic equipment in order to reduce the mass [1]. Mg-14Li-1Al (LA141) alloy has the density of 1.35−1.40 g/cm^3 and has excellent plasticity due to its full BCC structure. Mg-5Li-3Al (LA53) is lighter than Mg-3Al alloy and has good plasticity because of its lower c/a value, although its structure is hexagonal close packed (HCP).

Mg-Li alloy is chemically active, and so far, the cast ingot is often prepared by common mould casting because of no usable continuous casting equipment. Therefore, the Mg-Li alloy cast ingot has the large grain size, which will decrease its plasticity and strength. The addition of Al or Zn with higher level [2], multi-element alloying [3] and composite reinforcement [4] could increase the strength, but the plasticity and lightness have to be sacrificed. Adding the master alloys containing metallic compounds into metal melt is a simple and convenient method to refine the grains, which has successfully been used for Al alloys [5], compared to equal channel angle processing [6] and rapid solidification [7]. It was shown that the addition of Al-Ti-B master alloy into LA141 [8] and Mg-3Al-1Zn alloys [9] and the addition of Al-Ti-C master alloy into Mg-3Al-1Zn [10] could refine the microstructures greatly.

In this work, in order to develop new available master alloys to refine full BCC structure LA141 alloy and full HCP structure LA53 alloy, commercial Al-3Ti-1C and Al-5Ti-1B master alloys are added into LA141 and LA53, respectively. The microstructures are characterized by optical observation and the mechanism of grain refinement is discussed in detail.

2 Experimental

The alloys used in this work were commercial LA141 (13.5% Li, 1.2% Al and balance Mg, mass fraction) and LA53 (5.1% Li, 2.8% Al and balance Mg) alloys prepared in induction furnace under argon atmosphere. Al-5Ti-1B and Al-3Ti-1C master alloys were commercial.

The alloys were melted in an induction furnace under argon atmosphere. Before being melted, the alloy was placed into a mild steel crucible together with the corresponding master alloy. Al-3Ti-1C was added into the LA141 alloy with the levels of 0.5%, 1.0%, 1.5% and

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2.0%, while 1.5% Al-5Ti-1B was added for LA53 alloy. After the alloy was melted, it was held at 650 °C for 10 min and then the alloy melt was put out from the crucible by means of argon drive and poured into a ferrous mould. For comparison, LA141 and LA53 alloys without master alloy were prepared under the same conditions.

Each of the samples for optical observation was cut at the same position. These samples were ground, polished and then etched. The grains of each sample were examined using optical microscopy, and the average grain size at the centre of each sample was measured using the linear intercept method.

3 Results and discussion

3.1 Effect of addition levels of master alloys on grain size of LA141 or LA53

The optical microstructures of the LA141 alloys without and with the additions of Al-3Ti-1C master alloy are shown in Fig. 1. Equiaxed grains without columnar grains with the mean grain size of 900 μm were observed in the LA141 alloys, because of the low cooling rate of the mould. Due to the addition of Al-3Ti-1C master alloy, the grain size of LA141 alloy was reduced obviously. When the addition of Al-3Ti-1C was 1.5%, the mean grain size of LA141 alloy was reduced to 400 μm, and the smallest grain size was brought out. Further increasing the addition of Al-3Ti-1C master alloy caused the grain size to increase at some degree. It is shown that the grain refinement efficiency of Al-3Ti-1C for LA141 alloy is limited, which may be caused by the release of latent heat during solidification [11, 12]. The variation of grain size with the addition of Al-3Ti-1C master alloy is shown in Fig. 2. For comparison, the variation curve of grain size of LA141 with Al-5Ti-1B addition [13] is also plotted in Fig. 2. Although the grain size of LA141 cast alloy containing Al-3Ti-1C is obviously different from that of LA141 cast alloy containing Al-5Ti-1B, their grain refinement efficiencies can still be comparable. It is demonstrated that Al-3Ti-1C master alloy had lower grain refinement power than Al-5Ti-1B for LA141 cast alloy, but its grain refinement effect is still notable.

Figure 3 shows the microstructures of full HCP structure LA53 cast alloy without and with the addition of 1.5% Al-5Ti-1B master alloy. It is observed that with the addition of Al-5Ti-1B, the grain size of LA53 cast alloy was reduced to 240 μm from 500 μm compared with that without the addition. Obviously, the grain refinement efficiency of Al-5Ti-1B addition for full HCP structure LA53 cast alloy is not as strong as Al-5Ti-1B for LA141 cast alloy [13].

3.2 Mechanism of grain refinement of LA141 or LA53 with master alloy

The grain refinements of LA141 and LA53 were caused by the addition of Al-3Ti-1C or Al-5Ti-1B master

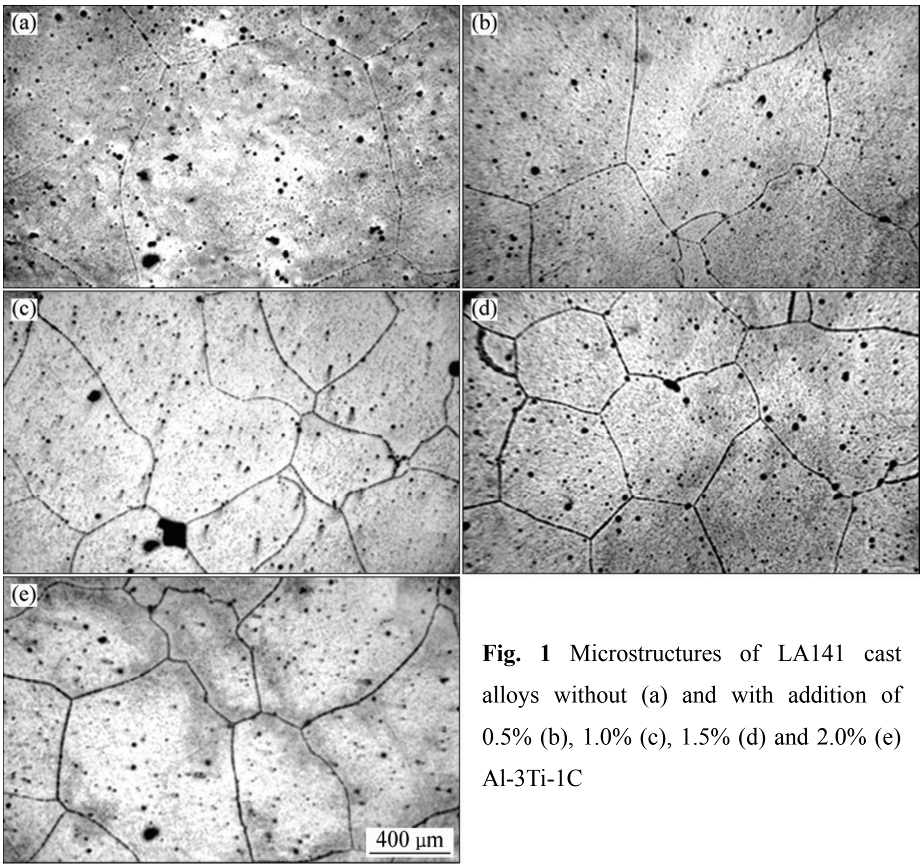

Fig. 1 Microstructures of LA141 cast alloys without (a) and with addition of 0.5% (b), 1.0% (c), 1.5% (d) and 2.0% (e) Al-3Ti-1C

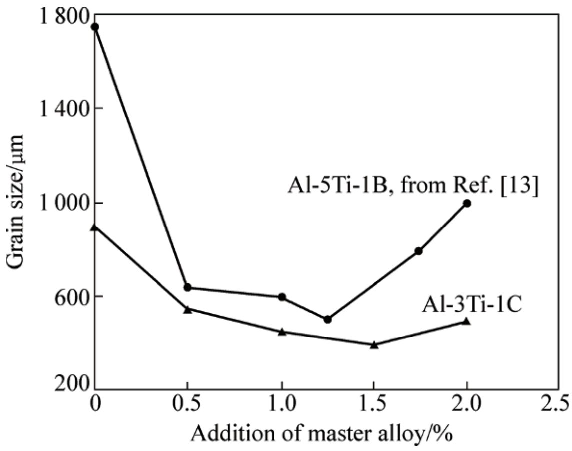

Fig. 2 Grain sizes of LA141 cast alloy with different additions of Al-3Ti-1C and Al-5Ti-1B

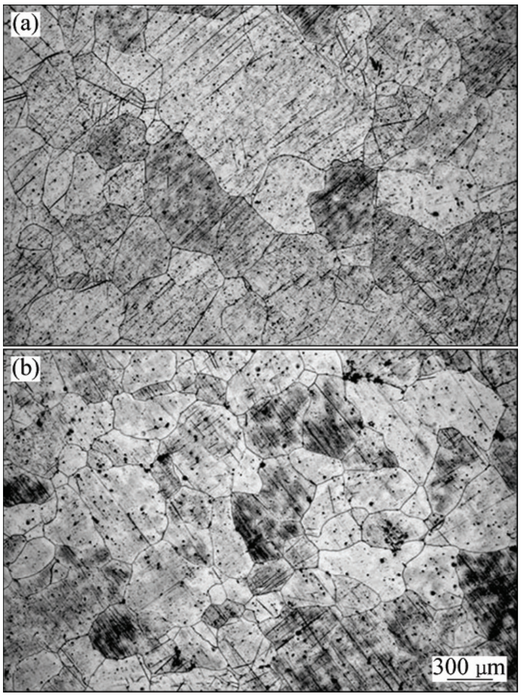

Fig. 3 Microstructures of full HCP structure LA53 cast alloy without (a) and with (b) addition of 1.5% Al-5Ti-1B

alloy which consists of Al matrix and metallic compound particles such as TiC or TiB_2. Therefore, the segregation of Al element in β-Li matrix of LA141 or in α-Mg matrix of LA53 during solidification, and/or the effect of metallic compounds should be the causes of the grain refinement.

When the addition of Al-3Ti-1C or Al-5Ti-1B was 1.5%, the content of Al in Al-3Ti-1C or Al-5Ti-1B was 1.2%−1.3%. In order to further clarify whether the content of Al in Al-3Ti-1C or Al-5Ti-1B has an effect on grain refinement of LA141 or LA53, the grain sizes of LA141 cast alloy without and with 1.2% Al addition were observed and compared, as shown in Fig. 4. The 1.2% Al addition has almost no grain refinement effect on LA141 alloy. Meanwhile, according to the previous study [14], the increase of Al content in Mg-12Li alloy with full BCC structure β-Li led to the grain coarsening. Therefore, the effect of Al content in the Al-3Ti-1C and Al-5Ti-1B master alloys on the grain size of LA141 alloy can be ignored. Here, the effects of TiC metallic compounds in Al-3Ti-1C master alloy on LA141 and the effects of TiB_2 in Al-5Ti-1B master alloy on LA53 should be taken account into.

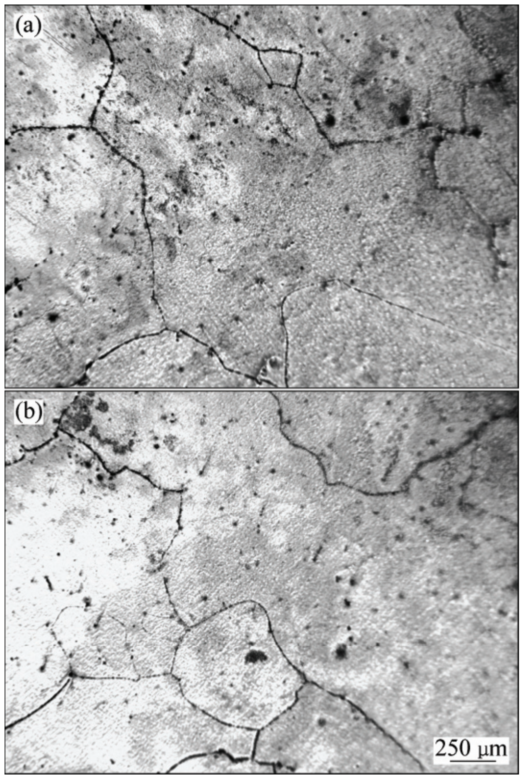

Fig. 4 Microstructures of LA141 cast alloys without (a) and with addition of 12% Al (b)

The edge-to-edge match model developed by ZHANG et al [15] is a simple and successful method to predict metallic compounds as efficient grain refiners [16] and to analyze the mechanism of grain refinement of Al alloys inoculated by metallic compounds [17]. In this model, it is necessary for a good grain refiner to have a less than 10% mismatch value (f_d) between the close packed or near close packed planes of the metallic compound and the matrix. Meanwhile, it is also necessary in the close packed or near close packed planes to have a less than 10% misfit value between the close or near close packed atom rows of the refiner and the matrix.

According to XRD PDF data [18], three close packed or near close packed planes of β-Li are identified as {110}, {211} and {200}, and those of TiC as {200}, {111} and {220}. Three close packed or near close packed planes of α-Mg are identified as {0002}, $\{10\bar{1}1\}$ and $\{10\bar{1}0\}$, and those of TiB_2 as $\{10\bar{1}1\}$,

$\{10\bar{1}0\}$ and $\{0001\}$.

Therefore, there are nine pairs of the potential matching planes of TiC/β-Li and TiB_2/α-Mg, respectively. The less than 10% f_d values between β-Li and TiC can be got according to the model and are listed in Table 1, and those between α-Mg and TiB_2 are listed in Table 2.

Table 1 Matching planes with less than 10% f_d between β-Li and TiC

Matching pair	f_d/%
$\{110\}_{Li}/\{111\}_{TiC}$	0.5
$\{211\}_{Li}/\{220\}_{TiC}$	2.036 8

Table 2 Matching planes with less than 10% f_d between α-Mg and TiB_2

Matching pair	f_d/%
$\{10\bar{1}1\}_{Mg}/\{10\bar{1}0\}_{TiB_2}$	7.3
$\{0002\}_{Mg}/\{10\bar{1}0\}_{TiB_2}$	1.0
$\{10\bar{1}0\}_{Mg}/\{10\bar{1}0\}_{TiB_2}$	5.3

The close or near close packed atom rows in these matching planes can be found by simulating the atom arrangement. In the $\{110\}_{Li}/\{111\}_{TiC}$ and $\{211\}_{Li}/\{220\}_{TiC}$ matching plane pairs, there is $\langle 111\rangle_{Li}/\langle 1\bar{1}0\rangle_{TiC}$ matching atom row with less than 10% misfit. Meanwhile, in the $\{10\bar{1}1\}_{Mg}/\{10\bar{1}0\}_{TiB_2}$, $\{0002\}_{Mg}/\{10\bar{1}0\}_{TiB_2}$ and $\{10\bar{1}1\}_{Mg}/\{10\bar{1}0\}_{TiB_2}$ matching plane pairs, there are $\langle 1\bar{2}10\rangle_{Mg}/\langle 0001\rangle_{TiB_2}$ and $\langle 1\bar{2}10\rangle_{Mg}/\langle 1\bar{2}10\rangle_{TiB_2}$ matching atom rows with less than 10% misfit.

Therefore, there are some crystallography orientation relationships (ORs) between β-Li and TiC and between α-Mg and TiB_2. The actual ORs need to be further studied through TEM or EBSD. Because of these ORs between metal matrix and metallic compounds, TiC and TiB_2 particles in the master alloys can be heterogeneous nucleation sites and act as effective grain refiners for β-Li and α-Mg respectively to refine β-Li or α-Mg matrix greatly.

4 Conclusions

1) Al-3Ti-1C master alloy is an effective grain refiner for the LA141 cast alloy with full BCC structure, and Al-5Ti-1B master alloy for LA53 cast alloy with full HCP structure as well. With the increase of the addition of Al-3Ti-1C master alloy, the grain size of LA141 cast alloy is reduced obviously, and the smallest grain size is 400 µm when the addition of Al-3Ti-1C master alloy is 1.5%. The grain size of LA53 cast alloy is reduced to 240 µm when the addition of Al-5Ti-1B master alloy is 1.5%.

2) The Al content in the Al-3Ti-1C and Al-5Ti-1B master alloys has basically no grain refinement effect on β-Li and α-Mg matrix. The mechanism of grain refinement of LA141 and LA53 cast alloys is mainly heterogeneous nucleation effect of TiC and TiB_2 particles in the master alloys, because of the ORs between metal matrix and metallic compounds such as TiC and TiB_2.

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